Assembly and Fabrication of Double-Curved Panel Structures Using Japanese Wood Joints Created with Desktop 3D Printers

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Abstract. This research presents a new direction for freeform structure assembly and fabrication through the collaboration of 3D printing technology and Japanese wood joining technology. Full-scale, self-build prototyping is demonstrated without glue or metal fittings. Rather than relying on digital fabrication machines to match the architectural scale, this study utilizes the Fused Filament Fabrication (FFF) with desktop 3D printers, which is the most widespread and inexpensive printing technology. By incorporating the perspectives of wood joinery and compact 3D printers, this study promotes a drastic change in 3D printed architectural production from a massive structure-oriented system to a module-oriented system. The project demonstrates how artisanal knowledge integrates with 3D printing architectural production by reconfiguring joint geometry, parametric modeling, fabrication, and assembly processes. We discuss our research process and final achievements, and we provide new ideas for architectural production using digital fabrication.

Keywords: Digital fabrication, Assembly, Japanese wood joints, 3D printing, Double-curved panel structure

1 INTRODUCTION

The development of digital fabrication is making innovative design and manufacturing possible for more people, and in the field of architectural production, new methods of joining and freeform modeling are being researched from various perspectives. Previous research has shown that the formability and compatibility of digital fabrication with parametric design tools have a profound impact on the creation of freeform geometry and complicated morphology in architectural production (Tang, 2006). This evolution in manufacturing has also generated construction methods other than traditional methods for examining structural issues (Kolarevic, 2003). As a practical study in the use of digital technology in the field of architectural production, many researchers are attempting the construction of freeform structures (Kolarevic, 2001).

Physically increasing the size of the processing machine, and processing larger components are solutions to architecture scale production that involve several disadvantages. There are two main fabrication methods used in digital fabrication research projects: the subtractive method and the additive manufacturing method. By using the subtractive method, large-scale freeform and detachable structures made with modularized architectural components (Schwinn et al.,2014). However, with the subtractive method, as the curvature and complexity of the components increase, the modeling time, cost, and waste directly increase (Raspall et al.,2020). However, with additive manufacturing, the use of large industrial 3D printers has enabled the efficient production of buildings with curved shapes (Lim et al 2016). Previous studies have shown the potential of large industrial 3D printing to reduce the human labor, construction time, and cost associated with architectural production (Beyhan & Arslan.,2018). Nevertheless, there is uncertainty regarding printing accuracy and the structural variability after construction. At the same time, this expensive equipment is not suitable for a viable open construction system in digital fabrication. Instead, the Fused Filament Fabrication (FFF) desktop 3D printer is the most widespread and affordable printing technology, and it has not yet been fully studied as a viable construction method. Additionally, the compact FFF 3D printer can fabricate freeform and complex morphologies more accurately than a large industrial 3D printer. In this context, it may be hypothesized that desktop 3D printers can overcome the weaknesses of the building production tools used in the above research. Therefore, this research takes a compact additive manufacturing machine as a solution for constructing architectural-scale structures by creating modularized architectural components accurately.

The printable build volume limit of the desktop 3D printer is an obstacle for full-scale prototyping. Thus, when creating an envelope of a certain size using small machining equipment, it is necessary to output multiple components and assemble them, and the joining techniques used in assembly are important (Sass, 2004). Japanese wood joints are a simplified assembly method for traditional wooden architectures that do not use glue or metal fittings. These joining techniques were carefully designed by artisans at the assembly order and usage location to create detachable architectural structures with sufficient rigidity (Uchida, 1993). The joining functions are limited by conventional fabrication technology, but they can be easily processed as double-curved panel components using FFF desktop 3D modeling. We adopted this assembly method as a key concept for 3D printing technology to realize the assembly and fabrication of freeform and detachable structures.

The goal of full-scale self-build prototyping is to evaluate the value of desktop 3D printers for the fabrication of freeform structures and to explore the possible use of Japanese wood joints as a method for the machined, detachable assembly of double-curved panel components. By introducing the perspective of Japanese wood joints and compact 3D printers, this research aims to promote a drastic change from massive structure-oriented systems to module-oriented systems in 3D printing for architectural production. This project tracks the design, manufacturing, and assembly phases, and develops essential tools and workflows. Furthermore, a description and a discussion on the digital design and manufacturing processes for integrating artisanal knowledge into 3D printing architectural production are provided.

2 BACKGROUND

Along with advanced digital fabrication technologies that drive powerful innovations in architectural production, traditional wood joint technologies are once again being designed and fabricated for highly customized assemblies (Yuan & Chai 2019). In particular, in several projects that use the subtractive method, both the design and production of wood joints are realized with high precision to accommodate small local variations that are difficult to achieve by hand. For example, Krieg et al. (2015) introduced the expansion and creation of a robotically fabricated, lightweight timber plate system. Robotic fabrication using the subtractive method has been shown to achieve the fabrication of individualized complex joints and make it possible to fabricate wooden plate structures.

On the one hand, the FFF desktop 3D printer can be used to fabricate components with complex geometries such as wood joints with high precision. Nevertheless, the most widespread and affordable digital fabrication equipment, the FFF 3D printer, has seen limited research efforts in the field of architectural production. Some of the architectural-scale work on FFF 3D printing are valuable precedents, including the Bloom (Rael & Fratello, 2015), the EGG Project (Hipolite, 2014), the Rise Pavilion (DeFacto, 2016), and Timescapes (Raspall et al.,2020). These studies and artifacts are configured with components fabricated by FFF 3D printers, yet they have not been examined from the perspective of assembly using wood joints.

The structure presented in this paper focuses on the combination of FFF desktop 3D printing and assembly using wood joints. Furthermore, the conclusions are based on a series of workflows through an architectural-scale prototype practice.

3 METHODOLOGY

The use of digital design and manufacturing tools was entirely under the control of the authors. We developed a complete digital and manufacturing workflow from the assembly strategy to full-scale prototyping.

This study was carried out in four major steps. First, to apply Japanese wood joints to a double-curved panel assembly, some joint geometries were reconfigured. The second step was to create a parametric paneling script that could generate components with interlocking joints in a 3D printable size from the designed 3D model. The third step involved fabricating each component using FFF desktop 3D printers. Finally, all 3D printed double-curved panel components were incorporated into a single project to evaluate the assembly strategies for execution by people who may not be familiar with the details of this project.

4 DOUBLE-CURVED PANEL STRUCTURE

A double-curved panel structure was designed to validate the detachable freeform production capabilities of the combination of affordable FFF desktop 3D printers and Japanese wood joint technology. The space was designed as a teahouse with a smooth, double-curved surface from the small entrance to the large opening, as well as the floor surface. The total footprint was 2.9 m2, so that 1.5 tatami mats could be installed, and the overall geometry envelope was H165 × W187 × L187 cm. The smooth freeform structure presented a manufacturing challenge as it needed to consist of double-curved panel components with a simplified interlocking assembly method and could not be

Figure 1. Exterior view of the project’s overall geometry Source: Kei Atsumi, 2021.

directly built from flat materials, as in the subtractive method. The overall geometry of the project is illustrated in Fig. 1.

This freeform structure design was modeled by Rhinoceros for compatibility with the parametric modeling software presented later and was used as the base to develop an assembly design for a fabrication process tailored to the use of an FFF desktop 3D printer and Japanese wood joint technology. The joint design for the panel components, 3D modeling method, fabrication, and assembly processes are described in the following subsections.

4.1 RECONFIGURING JAPANESE WOOD JOINTS

In digital aid, the complexity of joint structure is no longer a problem. At this stage, we focused on how to reconfigure the original Japanese wood joining rules and geometry. Design in a digital environment not only overcomes the limitations of the fabrication method for traditional wood joint structures but also creates a novel assembly strategy with three-dimensional thinking to facilitate the construction of freeform structures. In this section, two joints are designed by reconfiguring conventional joints.

The joint design for the floor and shell section components (Fig. 2a) was obtained from the Hozo and Sen in the Japanese wood joints (Fig. 2b). The joining mechanism for each component was considered in addition to the assembly strategy (Fig. 2c). The utility of the designed joint geometry was confirmed using physical test prototyping (Fig. 2d)

The joint design connecting the shell structure components (Fig. 3a) was from Ryakukama and Sen Japanese wood joints (Fig. 3b). The joining mechanism of the components was also designed to be suitable for joining double-curved panels (Fig. 3c). Through physical test prototyping, the appropriateness of the joint geometry was verified (Fig. 3d).

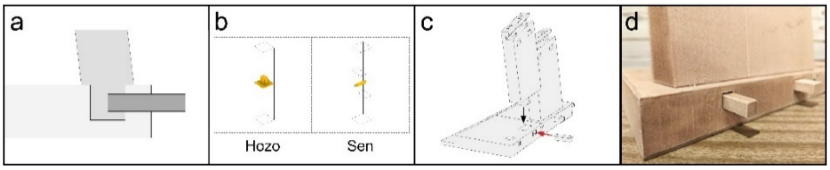

Figure 2. Joint design section for the floor and shell section components (a), Joint references : Hozo and Sen from Japanese wood joints (b), The joining motion diagram (c), Physical test prototyping (d) Source: Kei Atsumi, 2021.

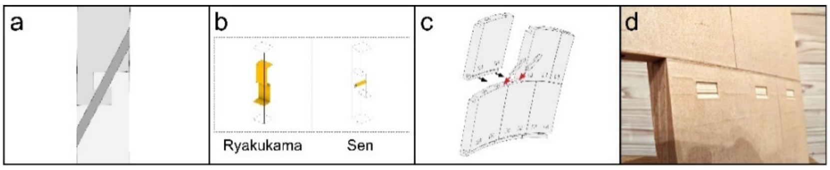

Figure 3. Joint design section for the shell structure components (a), Joint references : Ryakukama and Sen from Japanese wood joints (b), The joining motion diagram (c), Physical test prototyping (d) Source: Kei Atsumi, 2021.

4.2 PARAMETRIC MODELING of PANEL COMPONENTS

In the previous section, we proposed a new joint design for joining components of freeform structures by reconfiguring traditional Japanese wood joints, assuming the high modeling performance of an FFF desktop 3D printer. Next, the digital 3D data of the joined components had to be generated from the designed structure for the 3D printing fabrication process. It was an extremely difficult task to divide the entire double-curved geometry into 3D printable sizes and then manually sculpt the wood joint structure accurately to fit each situation, as it required many complex 3D modeling processes. In this section, we describe the process of efficient and accurate digital modeling by creating a parametric paneling script.

A series of calculation processes were created using Grasshopper, a parametric modeling tool in Rhinoceros that generates digital 3D data based on freeform modeling geometry (Fig. 4). First, the freeform modeling geometry was inserted into the script as base information, and then it was divided into brick tiles to fit inside a bounding box of W280 × D250 × H300 mm, which was the maximum output volume of the desktop 3D printer that was used. After logically dividing the freely curved surfaces into appropriate sizes, every shell structure component had a unique double-curved panel shape. Then, the cross-sectional shape of the wood joints designed in the previous section was mechanically modeled along the top and bottom edges of each divided double-curved panel component. By adding the complex wood joint's geometry to the double-curved panel components, we were able to create digital 3D data for detachable freeform structure architectural components that could be fixed tightly without the use of glue or metal fittings.

Each component was assigned a file name and an engraved ID in the 3D data, making it easy to control the order and position of many uniquely formed components in the manufacturing and assembly processes. A simplified representation of each component by ID was also planned for self-assembly practice by people who were not familiar with the project. The file format was finally converted to STL for inputting the 3D model data created in Grasshopper into the desktop 3D printing software. During this process, it was necessary to pay attention to the tolerance setting to prevent subtle dimensional differences during the output of the joint components.

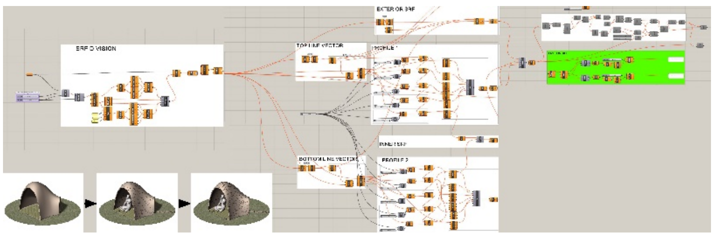

Figure 4. The parametric paneling script by Grasshopper Source: Kei Atsumi, 2021.

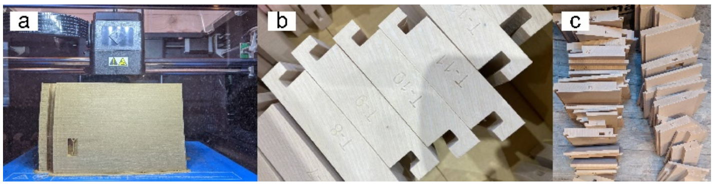

Figure 5. Photo of FFF desktop 3D printed components (a), Detailed view of printed components (b), The variety of components shapes (c), Source: Kei Atsumi, 2021.

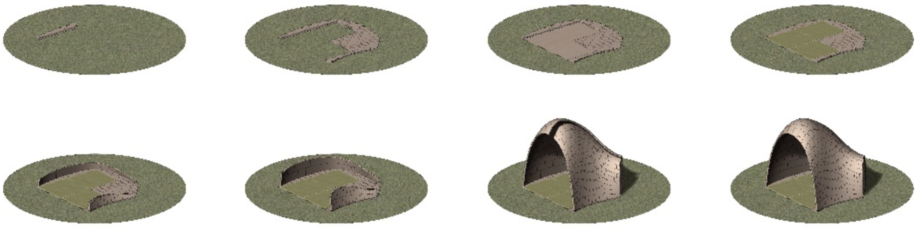

Figure 6. The diagrams of the assembly process Source: Kei Atsumi, 2021.

4.3 FABRICATION with THE DESKTOP 3D PRINTER

After the design of the structure was completed in the digital environment, the digital fabrication tool could be used to verify that the structure could be assembled by practicing the physical model. In this section, we introduce the methods and processes for the physical fabrication of digitally generated 3D models. One of the reasons we chose to use the FFF desktop 3D printer in this research is its high formability. However, printing double-curved panel components with wood joint geometry is a challenging task because of the complexity and novelty of the form itself. Therefore, a detailed manufacturing plan is required. Approximately one thousand unique pieces needed to be printed and managed accurately so that they could be correctly transferred to the assembly process. The digitally designed and generated components were printed by six FFF desktop 3D printers running in parallel and, 24/7 for eight weeks. Furthermore, the printing of all components ensured that the design of the components was within the printable size according to the parameters of the paneling script (Fig. 5).

4.4 ASSEMBLY

We believe that the open construction system proposed in this study, which is a combination of desktop 3D printer technology and Japanese wood joint technology, can be demonstrated by performing all workflows without the help of construction experts. From this perspective, the self-build assembly experiments were carried out. In this section, we describe the process and details of the assembly experiment.

The assembly experiment was carried out by four regular workers and one designer who engaged in manual assembly. A diagrammatic description of the assembly process is shown in Fig. 6.

First, the floor panels, which provided the foundation for the entire structure, were assembled. Later, tatami mats were installed in the 1.5 tatami mat space that had been planned in the design process.

Second, the joining of the floor and shell components was completed. The reconfigured joinery, which is a composite of the traditional Japanese wood joints "Hozo" and "Sen", was observed to produce sturdy three-dimensional joints with accurate 3D modeling and printing.

Finally, a freeform shell that enclosed the teahouse space was assembled. Reconfigured joinery based on "Ryakukama" and "Sen" traditional Japanese wood joints was useful for joining double-curved panel components. Accurate 3D modeling and printing allowed for the tight assembly of each component. A smooth freeform structure was realized from the bottom to the top. Finally, a double-curved panel structure was created by fitting the uppermost panel component in the middle.

The self-built assembly experiment was completed in approximately six h without the use of glue and metal fittings (Fig. 7). Because of the high level of geometric accuracy of the 3D printed components, the fitting of the components was quite accurate.

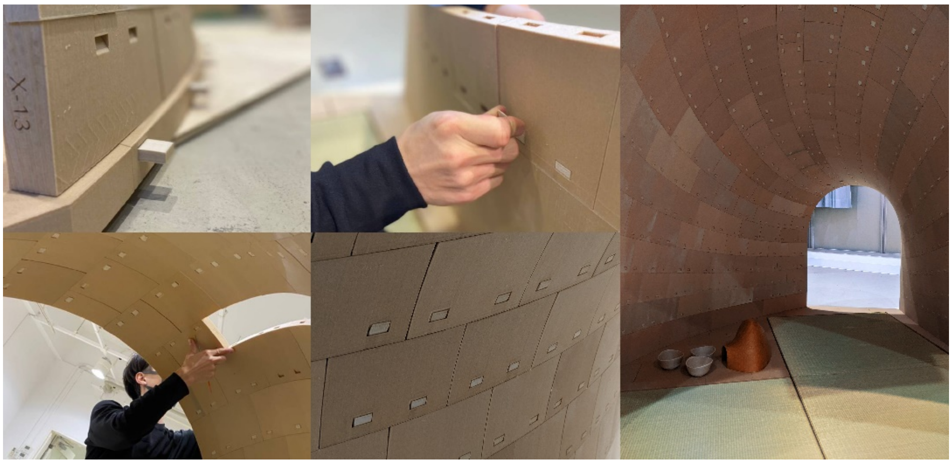

Figure 7. Photographs of the assembly Source: Kei Atsumi, 2021.

5 RESULTS and DISCUSSION

The results of this project indicate that the FFF desktop 3D printer is a viable fabrication tool for the production of architecture-scale freeform structures, and the Japanese wood joint technique can be integrated as a machine-crafted assembly method for modularized freeform architectural components using a digitally-aided design process. Instead of relying on digital fabrication machines tailored to architectural scale, this research project was the first attempt to realize a full-scale, freeform, detachable structure through a combination of desktop 3D printing technology and Japanese wood joinery reconfiguration.

With the aid of the FFF desktop 3D printer, traditional wood joining has taken on a new form that providing direction for the assembly of freeform structures. Through the three guidelines in this design process, the original function of Japanese wood joinery is retained so that the direction of reconfiguration can be clarified. A parametric paneling script was developed for the fabrication process, allowing for accurate 3D modeling of the double-curved structure and complex joint geometry of approximately one thousand unique components. The completion of the prototype demonstrated that the double-curved panel structures could be tightly assembled by self-build practice while retaining their detachability through the synthesis of reconfigured Japanese wood joinery, a parametric modeling process, and compact additive manufacturing fabrication technology.

This research utilized a series of workflows from digital design practice to physical manufacturing practice to explain the development of our hypothesis. The compact FFF 3D printer provides a method to assembling an architectural scale freeform structure. We have clearly explained and described the process of this research and presented an open construction system that provides new ideas for the assembly and fabrication of freeform structures in the architectural production field with digital fabrication.

However, it must be mentioned that the application of 3D printed panel assembly methods to real-world construction is still limited by building regulations. Further experiments and practices are needed to improve the joining functions against various forces, and to improve the durability and fire resistance, and insulation performance of the components, and so on, to further explore the advantages and practical value of module-oriented systems in 3D printed building production. From this project and many related studies, we speculate that traditional artisanal knowledge, combined with digital-aided 3D modeling design and affordable digital fabrication technologies, will occupy an increasingly important place in innovative digitally oriented architectural production, promoting the emergence of more efficient and practical open construction systems.

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